Acquisition and Production of Skilled Behavior in Dynamic Decision-Making Tasks:

Final Report

for

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Principal Investigator:

Alex Kirlik
School of Industrial and Systems Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0205

Overview

This report contains summaries of the four projects completed during the performance of this research. The four projects described are:

1. Perceptual Augmentation Aiding for Situation Assessment

2. Perceptual Augmentation Aiding for Dynamic Decision-Making and Control

3. Action Advisory Aiding for Dynamic Decision-Making and Control

4. Display Design to Support Time-Constrained Route Optimization

Papers based on each of these projects are currently in preparation. The theoretical framework upon which the first three projects are based, Ecological Task Analysis, was also developed during the performance of this research, and is described in a previous report, and can also be found in Kirlik (in press), Requirements for psychological models to support design: Toward ecological task analysis, in Flach, Hancock, Caird, and Vicente (Eds.), *The Ecology of Human-Machine Systems*. Erlbaum. A project concerned with modeling strategies in human control of a dynamic system was also completed during the performance of this research, and is described in Kirlik (1993), Modeling strategic behavior in human-automation interaction: Why an "aid" can (and should) go unused, *Human Factors*, 35(2), 221-242. The following graduate students's research was supported either all or in part, by this research:

1. Ling Rothrock, MS, Ind & Sys Eng, 1991. Currently working toward PhD.

2. Merrick Kossack, MS, Ind & Sys Eng, 1992. Currently with CTA. Inc.

3. Laura Moody, PhD, Ind & Sys Eng. 1993. Currently Asst Prof at Mercer University.

4. Wendy Markert, PhD, Ind & Sys Eng, Expected 1994.

5. Wes Krosnick, MS, Ind & Sys Eng. Expected 1994.

Perceptual Augmentation Aiding for Situation Assessment

Alex Kirlik, Georgia Institute of Technology

Problem definition

In a variety of technologically complex environments, a major contributor to cognitive demands appears to be the presence of perceptually impoverished displays which provide only an opaque window to the task at hand. Such interfaces may require the operator to meet significant demands in order to develop and maintain an active understanding of the state of the task system (i.e., situation assessment) and also to ensure that action selection is consistent with both goal-centered and environmentally-centered constraints on productive behavior (i.e., dynamic decision making). The problem of "situation awareness" in modern vehicular control systems is a prime example of a limitiation on skill acquisition and performance apparently due to the lack of perceptual information at the interface capable of adequately specifying the environmental state and constraints on productive behavior.

Given this observation, it is natural to wonder how much the acquisition of skill could be accelerated and final performance improved if the operator was provided with information displays which better specify both the state of the environment and the constraints to which action selection must be sensitive. We present research which attempts to address this question in the context of a dynamic laboratory decision and control task, the Extended Joint Surveillance and Target Attack Radar System (EJSTARS). First, task analysis was performed to identify a set of environmental and goal-centered constraints on productive action. Information capable of specifying these constraints was not found to be readily perceptible on the original EJSTARS display. Therefore, a second, perceptually augmented display was created which provides graphical information capable of specifying three environmental and one goal-centered constraint on productive behavior. An experiment was performed to evaluate the potential benefits of the perceptual augmentation approach in terms of enhancing both skill acquisition and peak performance. Since it is not always possible to enhance the actual displays in an operational environment, the experiment was designed to also evaluate training in terms of the ability of the augmented displays in the training system to support skilled decision and control performance even after the perceptual augmentation is removed.

Domain description

The research domain is a hypothetical information-gathering-and-attack system, referred to as the Extended Joint Surveillance and Target Attack Radar System (EJSTARS). It consists of a terrain-filled battlefield environment consisting of stationary friend targets that must be protected from unidentified enemy war-vehicles. These vehicles are located using an orbiting radar plane and may be identified or destroyed using unmanned aerial vehicles (UAVs), all of which are controlled by a single operator from an interface inside a ground control station. The laboratory simulation is implemented on an Apple Macintosh Quadra 700 computer. A Radius PrecisionColor 19" monitor is used at 1152 x 870 resolution. All input occurs on a standard mouse input device. The computer language used for the simulation is Aldus' SuperCard 1.6. All 3-D graphics and animations are programmed using Specular International's Infini-D 2.0.

Task analysis

A task analysis based on the framework described in Kirlik (in press) was performed on the EJSTARS task. In this approach, the task is described in terms of the constraints upon productive action selection. The constraints may be both environmentally-centered (whether actions are consistent with the environmental structure), and goal-centered (whether actions are

consistent with task goals or payoff structure). The operator's task can then be considered to be selection of action which is mutually consistent with both these internal and external constraints. A display can therefore be evaluated in terms of the degree to which it makes perceptual information available capable of specifying these constraints. A process modeling approach which was successful in mimicking dynamic decision and control behavior based on such an approach is presented in Kirlik, Miller, and Jagacinski (1993), and a demonstration of the utility of this approach for display aiding in a dynamic decision and control task is presented in Kossack (1993).

Constraint identification

The first step in the task analysis is the identification of the environmental and goal-centered constraints to which behavior must be sensitive in order to be productive. The results of the task analysis suggested that three environmental, and one goal-centered, constraints were crucially important in the selection of action. The environmental constraints are:

    1. Constraints governing the locomotion of vehicles through the terrain.

    2. Constraints governing the distance enemy tracks can fire weapons.

    3. Constraints governing the penetrability of friendly armor by enemy weapons.

The goal-centered constraint is:

    4. Constraints governing the relative value of enemy and friendly objects in terms of the task payoff structure

Constraint 1 (locomotion) creates lawful regularities in the environment concerning possible paths of vehicles as a function of terrain (e.g., mountainous, level, ice covered). The operator must be sensitive with this constraint in order to correctly determine which enemy vehicles pose a threat to various friendly assets and which vehicles do not.

Constraint 2 (weapons range) creates lawful regularities in the environment concerning the ability of enemy vehicles to attack friendly assets as a function of distance between the enemy and friendly. As was the case with the locomotion constraint, the operator must be sensitive to this constraint in order to correctly determine which enemy vehicles pose a threat to various friendly assets and which do not.

Constraint 3 (penetrability) creates lawful regularities in the environment concerning the ability of enemy vehicles to attact friendly assets as a joint function of the friendly armor thickness and the potency of enemy weapons. Once again, the operator must be sensitive to this constraint in threat/non-threat discrimination.

Finally, even after all these constraints have been taken into account, it is quite possible that the environmental constraints underdetermine productive action, in that multiple threats may be encountered at the same time. In such cases, the operator must also select action in a manner sensitive to the payoff structure of the task, expressed above as Constraint 4. This final constraint allows the operator to select the most valuable action from the set of actions which are consistent with the three environmental constraints at any one time.

Display evaluation

The second step in the task analysis is the evaluation of the information display with respect to how well it supports the perceptual specification of the constraints identified above. The baseline EJSTARS display is shown in Figure 1. It was found that although the baseline display did provide information pertaining to all the task properties relevant to the four constraints, it did not provide integrated, relational information which could be directly used to select action in a

manner consistent with these constraints. An evaluation of the baseline display with respect to each of the four constraints is given below:

Constraint 1 (Locomotion):

The display provides terrain information in a graphical format (e.g., the actual EJSTARS display is a digitized photographic map of actual terrain). The display also provides information pertaining to each vehicle type on a call up basis. Vehicle type information, in combination with terrain information, determines where a vehicle can successfully locomote (e.g, certain vehicles can locomote over rocky or icy terrain while others cannot). Thus, while the display provides information that can be used to infer where a particular vehicle can and cannot locomote, the display does not provide the relational, integrated information that would allow locomotion possibilities to be perceived.

Constraint 2 (Weapons Range):

The display provides information on the location of the friendly assets and enemy vehicles through the use of icons superimposed upon the map. The display also provides information pertaining to the weapons range of each vehicle type on a call up basis. The distance between the friendly asset and and enemy vehicle, in combination with the weapons range information for the enemy vehicle, determines whether or not a a particular enemy vehicle poses a threat to a particular friendly asset at a particular time. Thus, while the display provides the information that can be used to infer whether or not a particular enemy can attack a particular friendly asset at a particular time, the display does not provide the relational, integrated information that would allow these attack possibilities to be perceived.

Constraint 3 (Penetrability):

The display provides information on the armor thickness of a friendly asset on a call up basis. The display also provides information on the potency of a given enemy vehicle's weapons on a call up basis as well. These two items of information, in combination, determine whether or not a a particular enemy vehicle poses a threat to a particular friendly asset at a particular time. Thus, while the display provides information that can be used to infer whether or not a particular enemy's weapons can penetrate the armor of a particular friendly asset, the display does not provide the relational, integrated information that would allow these attack possibilities to be perceived.

Constraint 4 (Payoff)

The display provides information on the number of personnel within every friendly vehicle and enemy vehicle and the dollar amount of these assets on a call up basis. The payoff function is a simple linear function of these variables, which decreases the operator's point total by a given abount each time a friendly asset or enemy vehicle is destroyed. Once again the display provides the information necessary to infer value and make tradeoffs between various potential actions, the actual payoff information is not present in a way that would allow these tradeoffs to be performed in a perceptual fashion.

Perceptual Augmentation

The results of the task analysis suggested a number of deficiencies in the design of the baseline EJSTARS display, as described above. In response, graphical forms capable of dynamically representing the relational information capable of specifying each of the four task constraints were constructed. Each of these graphical forms appears as on overly on the baseline

EJSTARS display. The enhanced EJSTARS display is shown in Figure 2. Perceptual enhancements corresponding to each of the four task constraints are shown in the Figure.

Locomotion Constraint:

The locomotion overlay provides a color-coded map in the vicinity of an enemy vehicle which directly indicates whether or not that vehicle can locomote at each world location. This color-coded map is shown in blue and red at the upper right of the enhanced display around track "BMP-1." The blue areas indicate where this track may locomote and the red areas indicate where this track may not locomote. Similar locomotion maps are available for other tracks on a call-up basis.

Range Constraint:

The weapons range constraint is indicated by a small black circle centered at the location of each enemy vehicle.

Penetrability Constraint:

The penetrability constraint is indicated by coding penetrability as the thickness of the black walls around each friendly asset icon. Thin walls around a friendly asset indicate that the currently selected enemy track does not have weapons capable of penetrating the given asset's armor, while thick walls indicate that the given asset is vulnerable to the selected enemy track's weapons.

Payoff Constraint:

Payoff information for each friendly asset is indicated with small bar graphs on each asset.

Evaluation

An experiment was performed to evaluate the effectivess of this perceptual augmentation approach for enhancing skill acquisition and peak performance. The experiment also investigated the ability of perceptual augmentation to serve as a training tool by using transfer conditions which removed the augmentation from the display, to measure the degree to which performance might suffer without the presence of the augmented information. The experiment used 8 subjects per each display group (baseline vs. augmented).
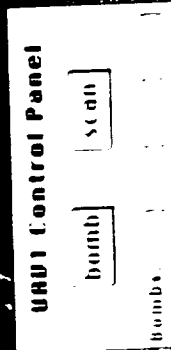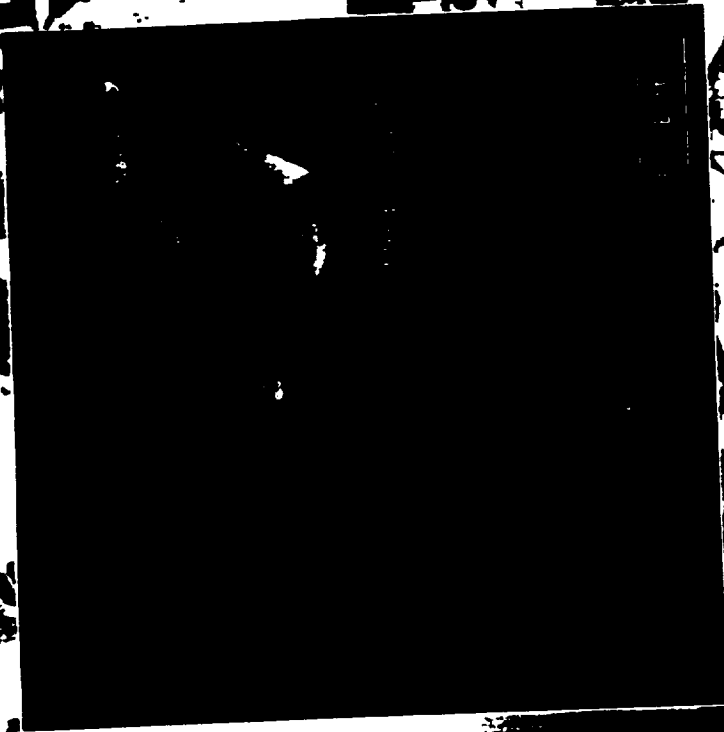
Results

Figure 3 shows the mean overall score for both display groups for sessions 1-18. The augmented display accelerated the acquisition of skill as this group performed better than the baseline display group during the first three experimental sessions. During sessions 17 and 18, the number of tracks was doubled in order to assess the effects of perceptual augmentation during high workload conditions. Interestingly, while the performance of the augmented display group did not suffer during the two sessions of increased workload, the performance of the baseline display group decreased during these sessions, suggesting that perceptual augmentation promoted more robust behavior than did the baseline display. Finally, sessions 19 and 20 were performed by the augmented display group after the perceptual augmentation was removed. Removal of augmented information did not decrease the performance of this group.

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Kossack, M. (1993) Ecological task analysis: A method for display enhancement. Unpublished M.S. Thesis, School of Industrial & Systems Engineering, Georgia Tech, Atlanta, GA 30332.
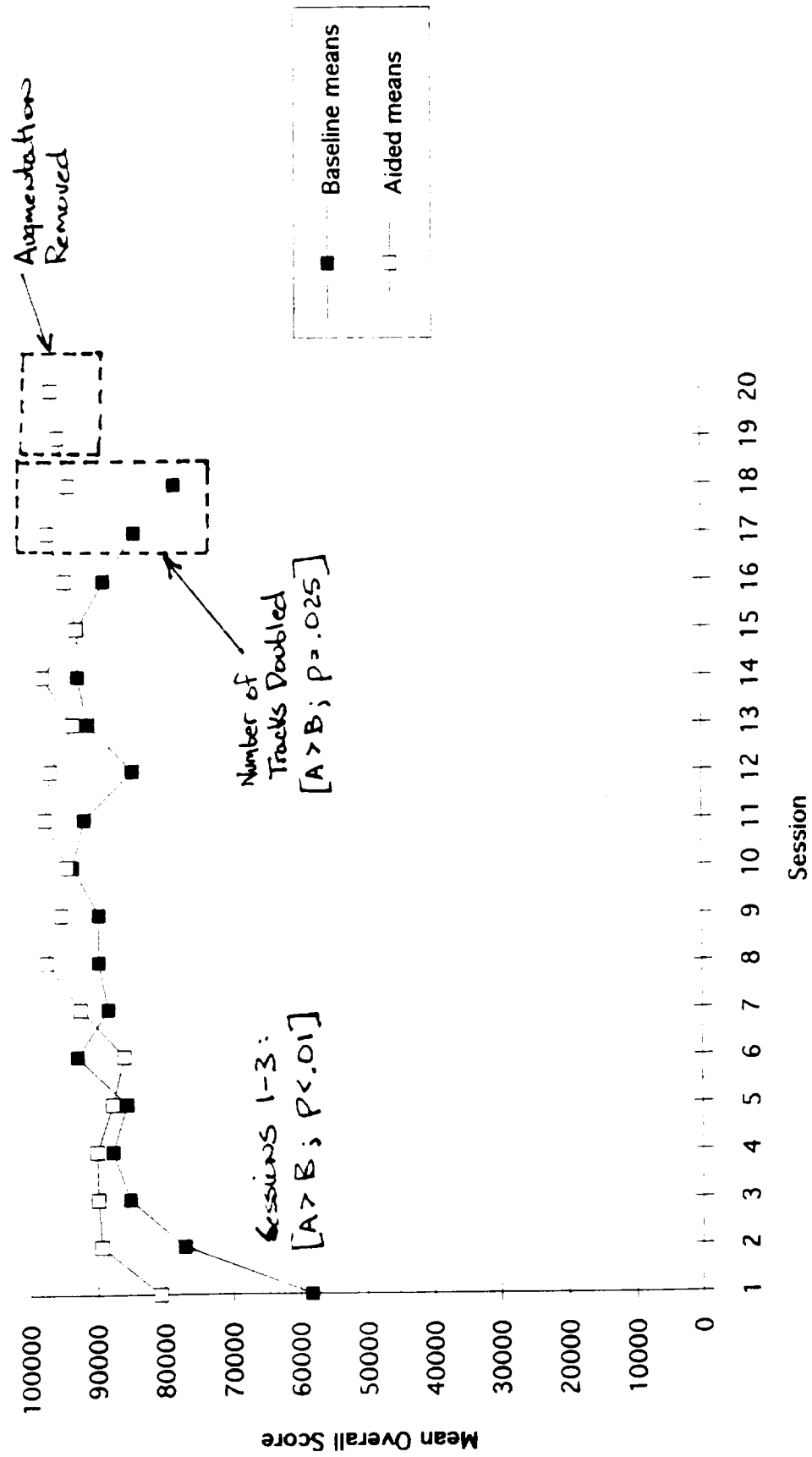
UAUI Scan Image

Open database | Cancel | Save for later

UAUI Control Panel

bomb | Scan

bombs

UAV1 Scan Image

[Open database] [Cancel] [Save for later]

UAV1 Control Panel

[bomb] [scan]

Bombs

Aided vs. Baseline Subject Mean Actual Scores

Augmentation Removed

Number of Tracks Doubled
[A > B; P > .025]

Sessions 1-3:
[A > B; P < .01]

Mean Overall Score

100000
90000
80000
70000
60000
50000
40000
30000
20000
10000
0

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20

Session

Baseline means

Aided means

Perceptual Augmentation Aiding for Dynamic Decision-Making and Control

Alex Kirlik, Georgia Institute of Technology

Problem definition

In a variety of technologically complex environments, a major contributor to cognitive demands appears to be the presence of perceptually impoverished displays which provide the operator only an opaque window to the task at hand. Such interfaces may require the operator to meet significant cognitive demands in order to develop and maintain an active understanding of the state of the task system (i.e., situation assessment) and also to ensure that action selection is consistent with both goal-centered and environmentally-centered constraints on productive behavior (i.e., dynamic decision-making). Many cases of "human error" in the control of technologically complex situations can be seen as stemming from the problem that readily available interface information does not well inform the operator about the environmental constraints upon acceptable solutions to decision tasks. In such situations, operators must keep knowledge of environmental constraints in memory (e.g., constraints upon acceptable flight routes, vehicle performance characteristics, states of automation, etc.) because information capable of specifying such constraints is not perceptually available. Operator solutions to decision tasks that fail to meet even one of the many environmental constraints governing acceptable system operation can often result in mission failure and potentially catastrophic consequences.

Given this observation, it is natural to wonder how much the acquisition of skill could be accelerated and human error reduced if the operator was provided with information displays which better specify the environmental constraints to which action selection must be sensitive. We present research which attempts to address this issue in the context of a dynamic laboratory decision and control task, StarCruiser. First, a task analysis was performed to identify a set of environmental and goal-centered constraints upon productive action in this task. Information capable of specifying all of these constraints was not found to be readily perceptible on the baseline StarCruiser display. Therefore, a second, perceptually augmented display was created which provides graphical information capable of specifying the the constraints upon each of the eleven primitive actions that comprise the StarCruiser operator's behavioral repertoire. An experiment was performed to evaluate the potential benefits of the perceptual augmentation approach in terms of enhancing both skill acquisition and peak performance. Since it is not always possible to enhance the displays in an operational environment, the experiment was designed to also investigate training issues in terms of the ability of the augmented display to support skilled decision and control performance even after the perceptual augmentation is removed.

Domain description

The research domain is a hypothetical exploration and resource acquisition task set in a space context. The task environment consists of a galaxy containing a number of solar systems to which activity is confined, and a spaceship under control of the subject. Each solar system contains a number of planets containing various amounts of scientific data and mineral resources, and it is the subject's goal to explore the galaxy to find these data and resources, to load them upon the StarCruiser, and to take them to a starbase to earn points. Constraints on time and fuel availability, and constraints governing acceptable ways of gathering data and resources provide the main source of dynamic decision-making complexity. The laboratory task is implemented on a Macintosh IIc computer with a Radius PrecisionColor 19" monitor. All input occurs with a standard mouse device. The computer language used for the task is Lightspeed C.

Task analysis

A task analysis based on the framework described in Kirlik (in press) was performed on the StarCruiser task. In this approach, the task is described in terms of the constraints upon productive action selection. The constraints may be both environmentally-centered (whether actions are consistent with the environmental structure) and goal-centered (whether actions are consistent with task goals or payoff structure). The operator's task can then be considered to be the selection of action which is mutually consistent with both these external and internal constraints. A display can then be evaluated in terms of the degree to which it makes perceptual information available capable of specifying these constraints. A process modeling approach which was successful in mimicking dynamic decision and control behavior based on such a theory is presented in Kirlik, Miller, and Jagacinski (1993).

Constraints on action

The set of eleven primitive actions available to the StarCruiser operator and any forms of perceptual augmentation used to better provide information about the constraints on these actions are shown below.

StarCruiser Action	Display Enhancements
1. Deploy collection tool	1a) Place tools on colored field 1b) Add background colors to tools 1c) X-out tools which cannot be deployed 1d) Dynamic coloring of depoyment string
2. Retrieve collection tool	2a) Dynamic coloring of retrieval string 2b) Used ghost images for collected commodities 2c) Realign StarCruiser capacity guages
3. Deploy probe	3a) X-out tools which cannot be deployed 3b) Dynamic coloring of deployment string
4. Retrieve probe	4a) Dynamic coloring of retrieval string
5. Place StarCruiser in orbit	5a) Add dynamic X to indicate 9th orbit radius 5b) Dynamic coloring to indicate orbit speed
6. Remove StarCruiser from orbit	No enhancements
7. Dock StarCruiser at StarBase	7a) Dynamic coloring to indicate docking speed
8. Release StarCruiser from StarBase	No enhancements
9. Change display view	No enhancements
10. Choose StarCruiser's destination	10a) Color coding of suns to indicate commodities 10b) Blue X for empty solar systems
11. Determine StarCruiser mode	11a) Dynamic coloring of StarCruiser outline

Each of the display enhancements listed above provides information about constraints upon the associated action that is not available on the baseline StarCruiser display. For example, placing tools on a field (1a) colored consistently with the color of the planets to which these tools can be

legally deployed provides information about constraints upon acceptable (tool, planet) assignments. Dynamic coloring of the deployment and retrieval strings (1d, 2a, 3b, 4a) indicate to the operator when a distance constraint (between the mouse cursor and a specified target) has been met to enable tool deployment and/or retrieval. Each of the other enhancements provides similar constraint-based information. A depiction of both the baseline(top) and perceptually augmented (bottom) StarCruiser displays is shown in Figure 1.

Evaluation

An experiment was performed using both baseline and augmented subject groups, with eight subjects per group. Each subject received initial training and then performed StarCruiser for 14 sessions. For sessions 15 and 16, subjects were also required to perform a concurrent mental arithmetic task in order to diagnose whether the augmented display lowered the cognitive demands experienced by subjects using the enhanced display. For sessions 17 and 18, subject groups switched displays, in order to diagnose whether subjects trained using the augmented skills would maintain their level of performance after removal of the augmented information.

Results

Figure 2 shows performance curves for both display groups for sessions 3-14 (sessions 1 and 2 were training sessions and were excluded from the analysis). Over these sessions, the main effect of display was significant with the augmented group performing better than the baseline display group. However, for sessions 13 and 14 only, the augmented display group and the baseline group did not differ in performance, suggesting that the primary benefit of the augmented displays in this experiment was the facilitation of skill acquisition.

A set of 12 additional performance measures were constructed to individually evaluate the effect of each of the 12 perceptual augmentations of the display. Here, it was found that 8 of the 12 display enhancements significantly improved performance of the augmented display group subjects, with the other 4 enhancements showing no effect on performance. The enhancements which proved to improve performance were:
 1. Dynamic coloring of deployment/retrieval string
  2. Realignment of StarCruiser capacity guages
  3. X indicating orbit radius
  4. Dynamic coloring of StarCruiser indicating orbit speed
  5. Dynamic coloring of StarCruiser indicating docking speed
  6. Coloring suns to indicate commodity levels
  7. Blue X indicating empty solar systems
  8. Dynamic coloring of StarCruiser to indicate mode

The results of the concurrent mental arithmetic sessions are shown in Figure 3. Although the graph indicates that the performance of the baseline group decreased 27% whereas the performance of the augmented display group did not change, this interaction did not reach significance. The results of the display-transfer sessions are shown in Figure 4, which indicates that neither group was affected by using the alternate display. Most interestingly, subjects using the augmented display, which was shown to facilitate skill acquisition in this task, did not suffer when the augmented information was removed.
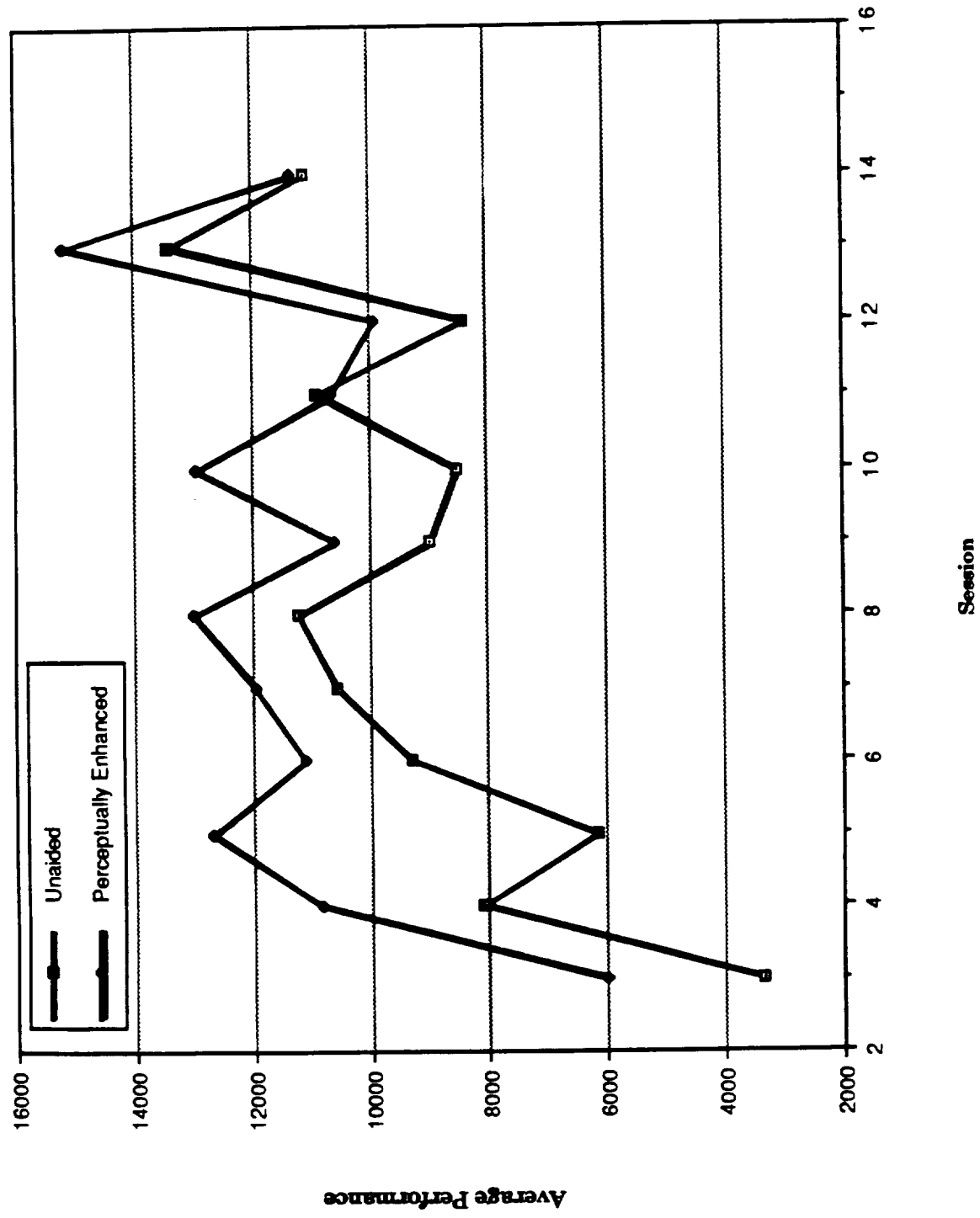
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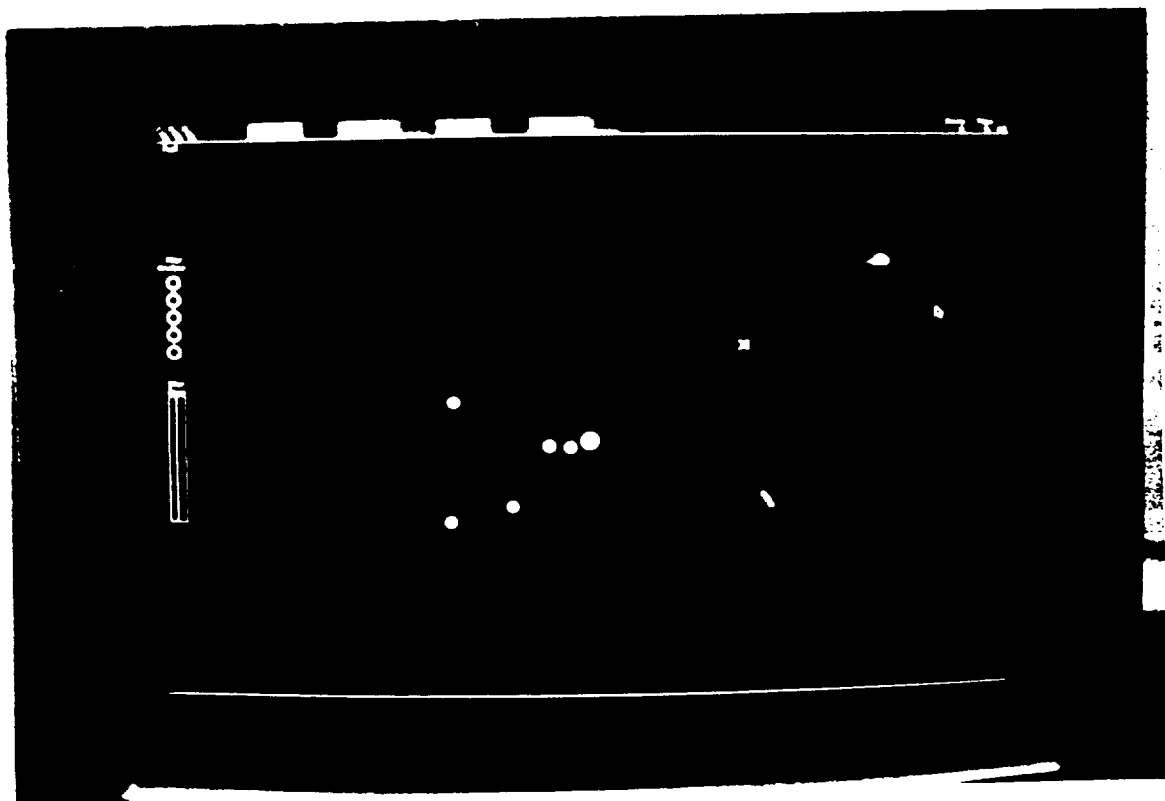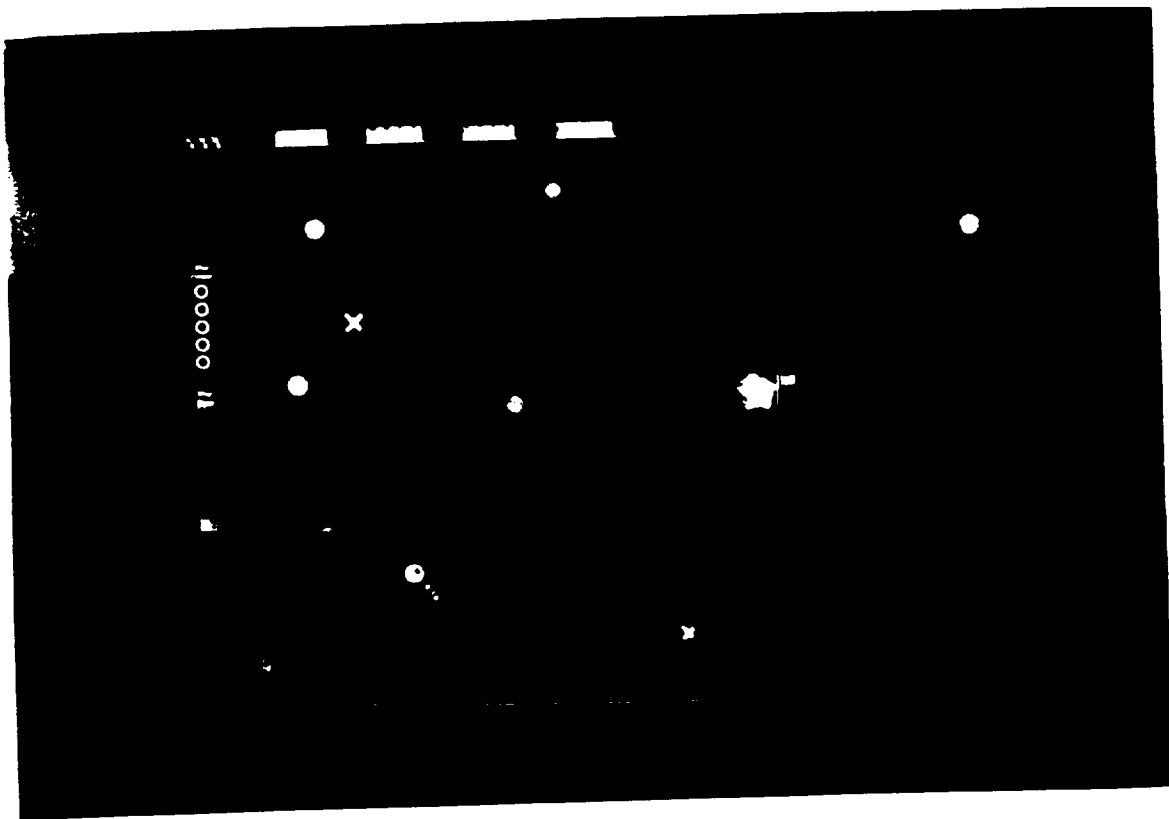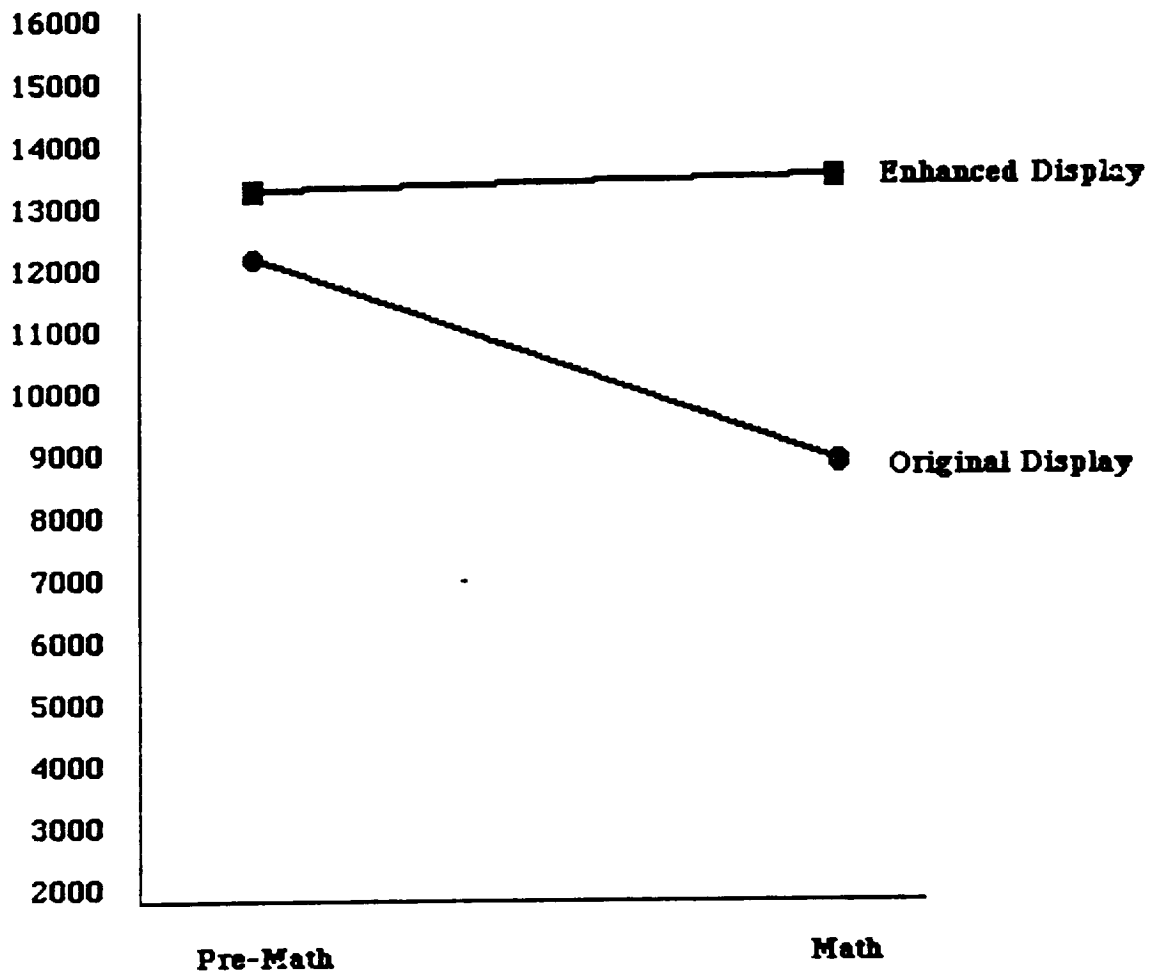
Performance of Unaided vs. Perceptually Enhanced Subjects

Effects of Concurrent Mental Arithmetic Task
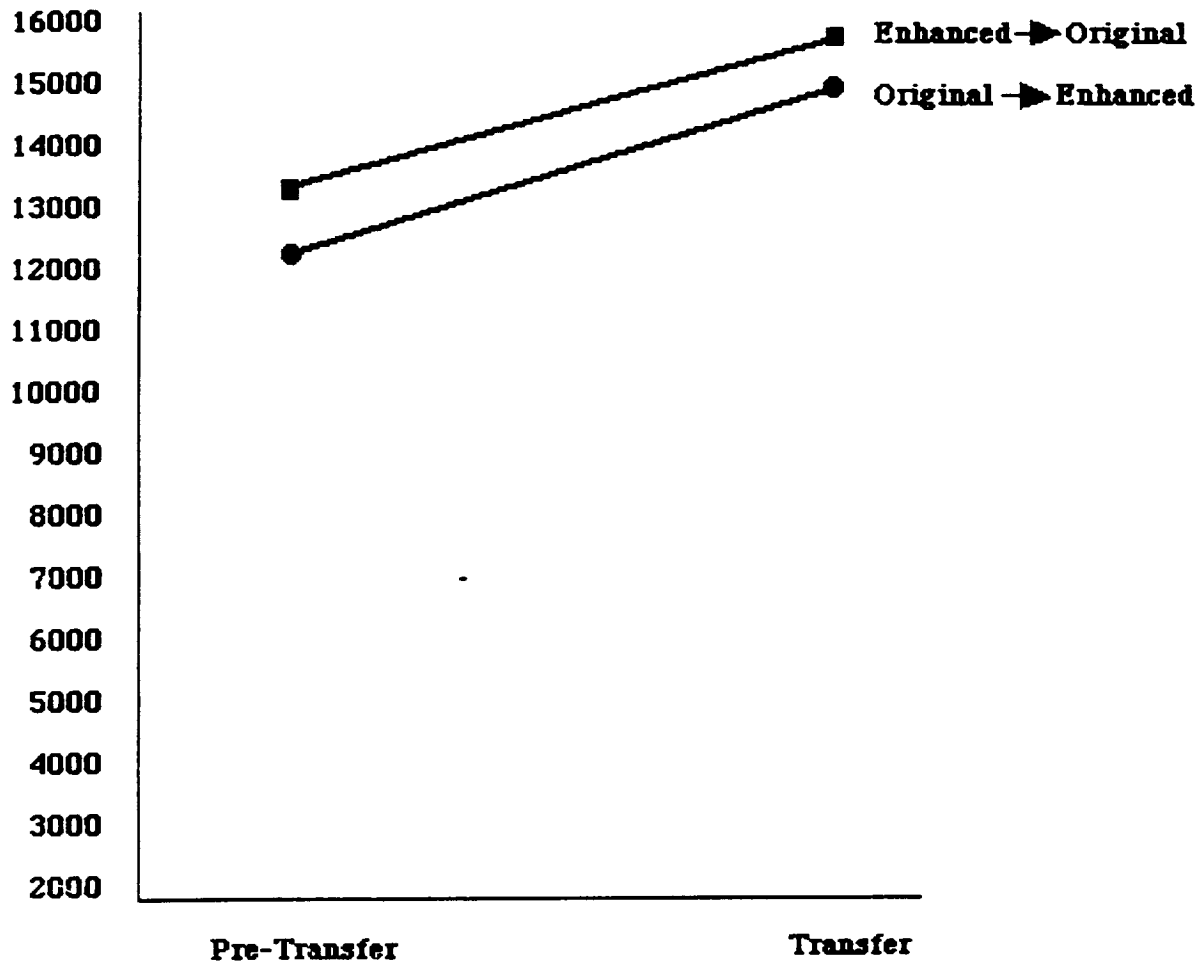
16000
15000
14000
13000
12000
11000
10000
9000
8000
7000
6000
5000
4000
3000
2000

Enhanced Display

Original Display

Pre-Math

Math

Transfer Results

Action Advisory Aiding for Dynamic Decision-Making and Control

Alex Kirlik, Georgia Institute of Technology

Problem definition

One approach for aiding human decision-making in complex human-machine systems is to provide the operator with a computer-based decision-aid which gives the operator advice by providing a dynamic, prioritized list of control actions which serve as recommendations. Presumably, the motivation behind this approach is that humans sometimes err in making decisions that could be better made by an algorithm implemented on a computer. However, it is recognized that in some cases the human will have access to information unavailable to the algorithm, so the human's task is not totally automated; rather, the human and computer are expected to work in tandem to hopefully produce performance superior to either the human or computer working alone.

Indeed, the design of the AERA family of aiding systems currently being considered for the US air traffic control system is based upon exactly this advisory aiding philosophy. However, a number of questions should be raised concerning the potentially effectiveness of this approach. Will the operator take the advice of the aid? Will human decision-making effectiveness degrade if the aid becomes temporarily unavailable due to technical failure? What will happen if the aid fails and gives faulty advice? In order to address questions such as these, an experiment was conducted using a laboratory dynamic decision and control task which compared the decision-making and control performance of a group of unaided subjects with a group of subjects for whom an action-advisory decision aid was made available. In addition to investigating the effect of the aid on skill acquisition and performance, the experiment also examined the effects of the aid becoming unavailable (both early and late in practice) and also the effect of the aid failing (providing erroneous advice) late in practice.

Domain description

The research domain is a hypothetical exploration and resource acquisition task set in a space context. The task environment consists of a galaxy containing a number of solar systems to which activity is confined, and a spaceship under control of the subject. Each solar system contains a number of planets containing various amounts of scientific data and mineral resources, and it is the subject's goal to explore the galaxy to find these data and resources, to load them upon the StarCruiser, and to take them to a starbase to earn points. Constraints on time and fuel availability, and constraints governing acceptable ways of gathering data and resources provide the main sources of dynamic decision-making complexity. The laboratory task is implemented on a Macintosh IIci computer with a Radius PrecisionColor 19" monitor. All input occurs with a standard mouse device. The computer language used for the task is Lightspeed C.

Action Advisory Aiding System

A window at the bottom of the StarCruiser display was created to communicate the advisory aid's dynamic list of recommended actions to the subject. The aid itself is based upon a model of human dynamic decision-making which has proved capable of high levels of performance in such tasks, and also of successfully mimicking human behavior (Kirlik, Miller, and Jagacinski, 1993). In the model, each of the primitive actions available in the StarCruiser task is evaluated at every time step with respect to two criteria: a) the degree to which the action is consistent with the current environmental structure; and b) the degree to which the action is consistent with current task goals. Simple linear and boolean functions measuring the degree to which these two classes of constraints are met are used to determine a scalar value indicating the desirability of taking each action at each point in time. In the aiding system, the top four actions with respect to this measure

are displayed to the subject in a prioritized list. The internal effectiveness of the aid was validated by creating a version of the aid which was capable of performing the StarCruiser task without human intervention. This version of the aid achieved scores comparable to those achieved by local expert subjects.

Experiment

An experiment was performed using both baseline (unaided) and advisory aid subject groups, with eight subjects per group. Each subject performed StarCruiser for 28 sessions. The first four sessions consisted of active training by the experimenter and were therefore excluded from analysis. In sessions 9 and 10, 19 and 20, and 27 and 28, for the advisory aid group, the aid was made unavailable by removing the advice from the display. In sessions 23 and 24 for the advisory group, the aid was intentionally designed to give faulty advice; in this case, the worst four possible actions rather than the best four possible actions were presented, as measured by the method described above.
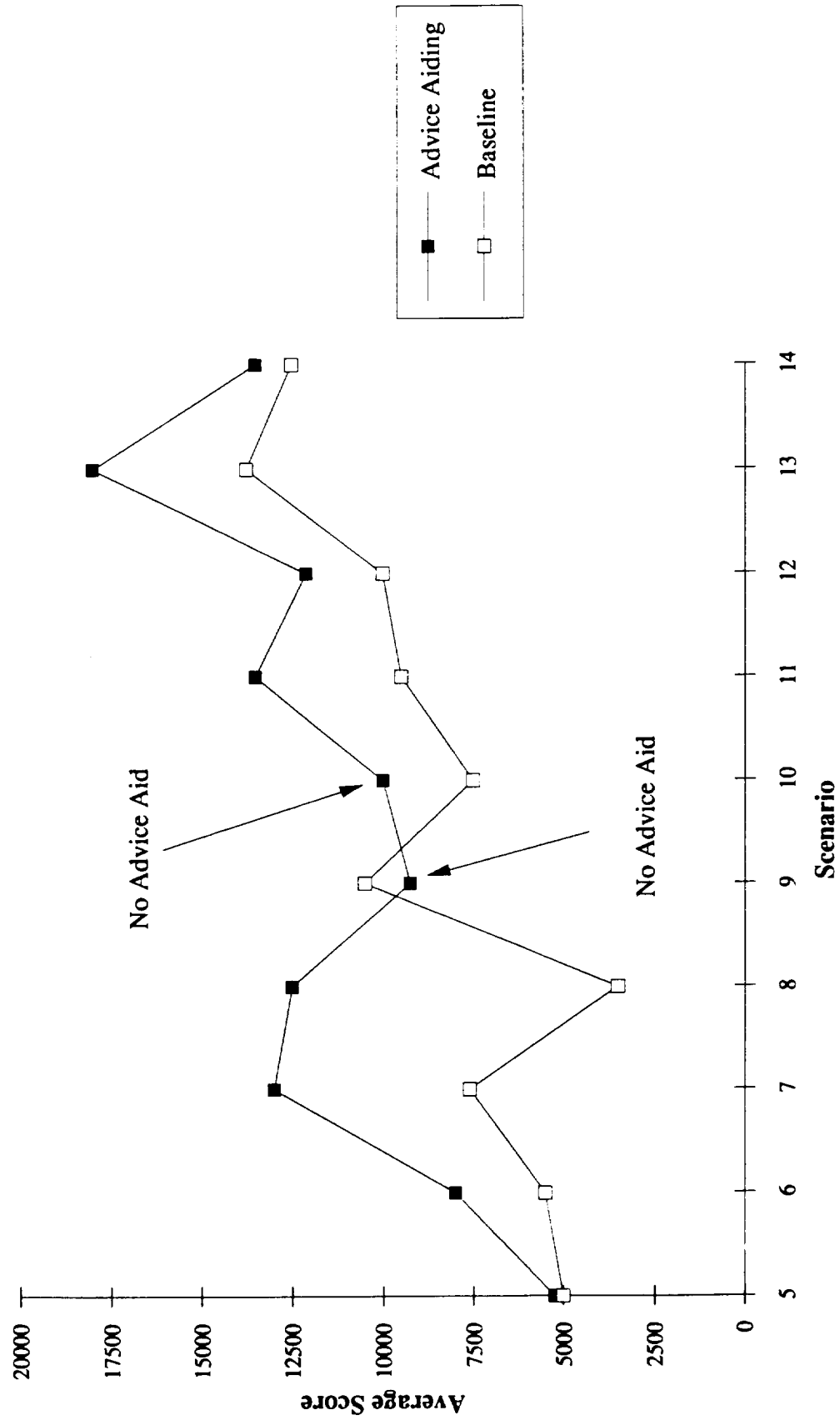
Results

Figures 1 and 2 show the mean performance of the two groups for the 24 sessions analyzed. The advice aid did have a positive effect on skill acquisition, as the aided group performed better than the unaided group over sessions 5-8 (the first four sessions after active training). There was some suggestion in the data that removal of the aid for sessions 9 and 10 decreased performance of the aided group although this effect was not statistically significant. Removal of the aid during sessions 19 and 20 (labeled 9tr and 10tr on the graph) and during sessions 27 and 28 (labeled 17tr and 18tr on the graph) had no effect on the performance of the aided subjects. Thus, while it is still an open question whether aid unavailability decreased performance very early in practice, aid unavailability clearly had no negative effect on performance after subjects had a good amount of experience performing the task. The optimistic interpretation of these results is that temporary unavailability of an advisory aid is of little concern. On the other hand, these results can also be interpreted to suggest that operators made very little use of the aid, especially late in practice, a conclusion that raises serious doubts about the ability of such an aiding system to compensate for faulty human decision and control performance.
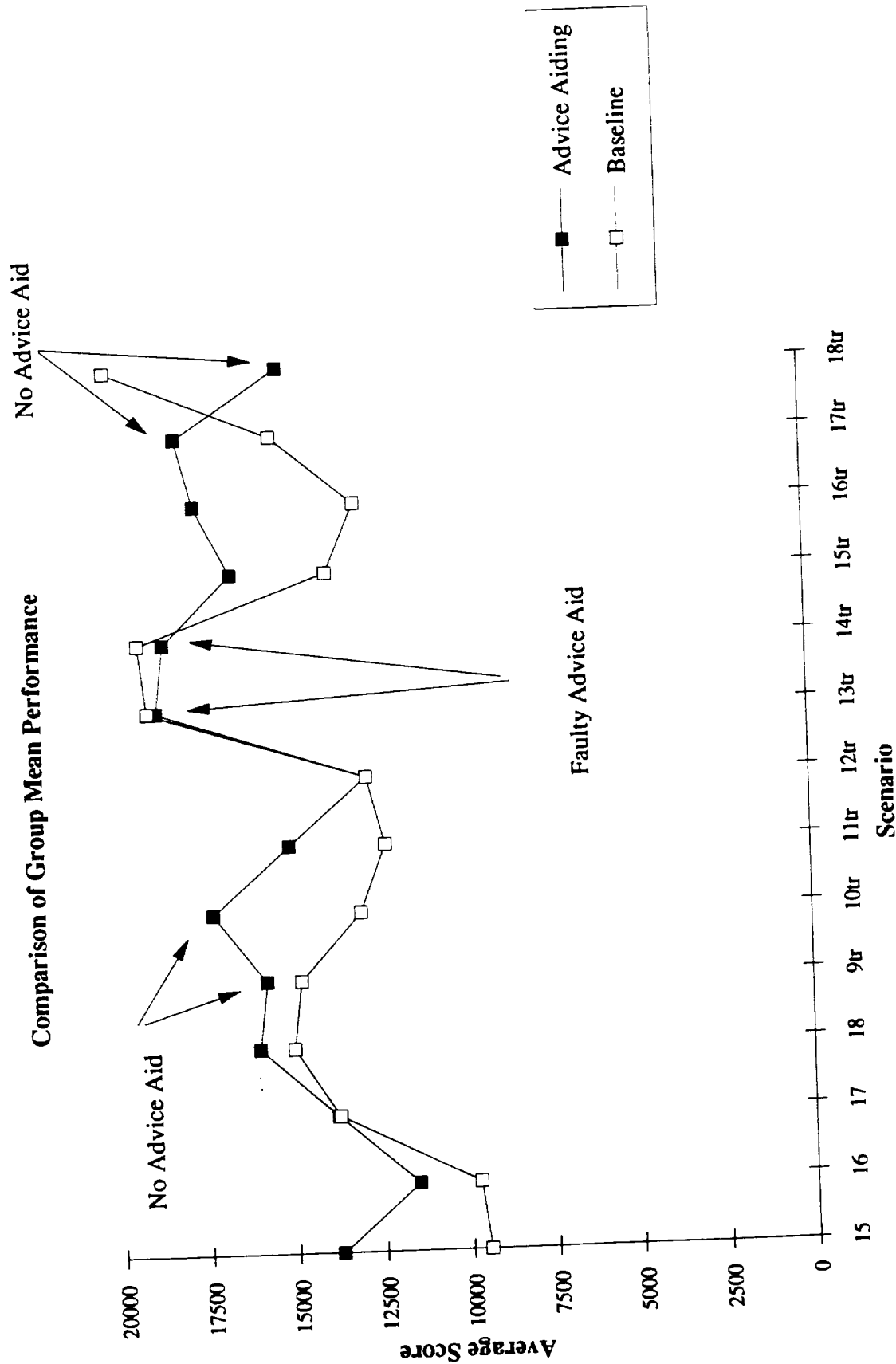
Indeed, the findings for sessions 23 and 24 (labeled 13tr and 14tr on the graph) are also consistent with the interpretation that subjects made little explicit use of the aid. Recall that in these sessions, the aid was designed to intentionally present faulty advice. However, clearly the subjects did not follow the faulty advice of the aid, as the performance of the aided group did not decrease during these two sessions. We also have anecdotal data concerning these two sessions that are quite relevant to achieving an interpretation of these data. Subjects were not informed in any way prior to these two faulty-aid sessions that these sessions were any different than those experienced previously. Only one of the eight subjects in the aided group made a spontaneous comment to the experimenter indicating that he realized that the aid was presenting faulty advice. Upon asking all eight subjects in the aided group after the completion of these sessions if they had noticed anything unusual, only one additional subject indicated that he realized that the aid was presenting faulty advice. Thus, six of the eight subjects apparently never even noticed that the aid had failed, lending support to the conclusion that these aided subject made very little, if any, explicit use of the information provided by the aid while performing at asymptotic levels of performance. Such findings raise serious doubts about the ability of such aids to compensate for poor human decision and control performance in tasks such as these.

References

Kirlik, A., Miller, R.A., and Jagacinski, R.J. (1993) Supervisory control in a dynamic uncertain environment: A process model of skilled human-environment interaction. IEEE Transactions on Systems, Man, and Cybernetics, Vol. 23, No. 4.

Comparison of Group Mean Performance

Average Score

20000
17500
15000
12500
10000
7500
5000
2500
0

No Advice Aid

No Advice Aid

5   6   7   8   9   10   11   12   13   14

Scenario

Advice Aiding
Baseline

Comparison of Group Mean Performance

No Advice Aid

No Advice Aid

Faulty Advice Aid

Advice Aiding

Baseline

Average Score

Scenario

15   16   17   18   9tr   10tr   11tr   12tr   13tr   14tr   15tr   16tr   17tr   18tr

0   2500   5000   7500   10000   12500   15000   17500   20000

Display Design to Support Time-Constrained Route Optimization

Alex Kirlik, Georgia Institute of Technology

Problem definition

A variety of human-machine systems require a human operator to create efficient solutions to constrained routing problems. Examples would be a logistics planner responsible for creating delivery truck routes to minimize travel costs, an emergency services dispatcher responsible for creating vehicle assignments and routes to minimize travel time, and an air traffic controller responsible for scheduling cost efficient routes for aircraft. Each of these problems differs in terms of the cost function the operator is attempting to minimize and also with respect to the constraints which determine the space of feasible solutions. However, these tasks all share the same general structure, which is that of a constrained vehicle routing problem. Such problems can sometimes be solved via operations research optimization techniques, however, most problems in operational environments are either too complex or else not sufficiently closed to enable a computer-based algorthmic solution to be found. In such systems, a technique called interactive optimization is frequently employed to allow a human to interact with an optimization system to presumably obtain problem solutions superior to those that could be achieved by either the human or computer acting alone. Design issues for interactive optimization systems can be expected to attract increasing attention as increases in computer power begin to allow some aspects of even very complex operational routing problems (e.g., terminal area flight route scheduling) to be treated algorithmically, thus creating a situation where more and more human operators will be asked to interact with computers to solve problems that were once the provence of human experts alone.

Although there is a large and rapidly growing number of papers on the design of interactive optimization systems in the operations research and logistics literature, rarely if ever do these papers ever refer to the vast literature on issues such as human problem-solving, human-computer interaction, and other issues which can be expected to be quite relevant to the effective design of these interactive systems. In our review of the interactive optimization literature, it became apparent that one reason for this disconnect is that the operations research community is simply unaware of the existing body of knowledge on psychological issues in design, as indicated by authors presenting ad hoc designs and solely intuitive justifications for these designs, as if a body of knowledge relevant to these decisions did not exist. However, it also became clear that the human problem-solving, human factors, and human-computer interaction literatures also had a role to play in this regard: the types of problem solving tasks addressed by these literatures are vastly oversimplified as compared to the types of problem solving tasks for which interactive systems must be designed to support human operators in operational environments. The purpose of the present research was to begin to bridge the gap between the tasks studied by both basic psychology research and human factors research, and the tasks faced by operators performing constrained vehicle routing problem-solving in operational environments.

Domain description

Vehicle routing problems (VRP's) in operational environments differ in at least two important respects from the types of problems which have given rise to both theories of human problem-solving (mostly well structured puzzles and games) and design guidelines to support problem-solving behavior (frameworks based on these theories). First, in a vehicle routing problem, one cannot describe problem-solving as the creation of a set of actions in order to move from an initial state to a goal state within a state space defined at a single (physical) level of abstraction. Even the simplest of VRP's, the Traveling Salesman Problem (TSP), requires the problem-solver to generate a solution (the shortest path connecting all destinations) which is not a single state in the physically defined problem space (such as can be done in games such as the Tower of Hanoi where the goal state is one of the many physically possible states of the puzzle).

Rather, in the TSP the goal is the shortest path, which is an abstract measure of goodness upon routes, which are themselves the objects capable of being represented in the physical problem space. Many different possible routes may result in the same measure of goodness, and the goal is to find any one of the many possible routes which minimizes travel distance. This difference in the formal representations of traditionally studied problem solving tasks and tasks such as the VRP creates many difficulties when trying to apply traditional problem-solving theories to VRP's.

A second critical difference between the VRP and the problem-solving tasks typically studied by researchers concerns the intensive perceptual nature of human interaction with the VRP. Existing problem-solving theories characterize mental activity as the construction of an internal problem representation, and all problem solving is done via the internal manipulation (e.g., means-ends analysis) using this representation. In the VRP, on the other hand, it is clear that perceptual activity, operating directly upon information in the external problem representation (or display), provides a crucial contribution to problem-solving activity. Various patterns and features of the display are recognized and perceptually structured, and problem-solving activity involving the manipulation of an internal representation seems to be called upon only when this perceptual mode of problem solving fails due to conflicts needing to be resolved by considering the problem in a more abstract fashion. For example, even a 100-destination TSP could be solved in a purely perceptual manner if the set of 100 destinations happened to be distributed in a clear, circular fashion, which would allow the problem solver to quickly sketch in the circle as the optimal route.

Given the desire to preserve these two features of VRP's that make them differ from the types of problems that have been traditionally studied, we chose the time-windowed VRP (VRP-TW) as the problem domain for this research. The VRP-TW is more complicated than the simple TSP in that each destination may have associated with it a time window that specifies the earliest and latest times at which the destination can be visited along the route. We chose the VRP-TW since it contains this additional time constraint characteristic of problems in many operational environments, and also because this time constraint creates a problem of such complexity that efficient algorithms for solving this problem are not available, thus necessitating an interactive optimzation design approach. Although this problem is much more complex than those problems which have motivated most cognitive theories of problem solving (and therefore is not readily amenable to analysis in terms of these theories), it is nevertheless still much simpler than most real-world VRP tasks. However, our goal in this research was to take initial steps at building a bridge between the basic and applied worlds of human problem solving, and we are not aware of any other studies of problem solving which have addressed a task of the complexity studied here.

Design approach

Our first studies in this research concerned humans solving the simple unconstrained TSP in order to motivate an understanding of how problem solving was performed in this perceptually intensive task. Our initial results indicated that problem solving appeared to be performed using extensive interaction between perceptual and higher-level cognitive activities. Since it appeared that the very efficient perceptual activities appeared to make a crucial contribution to performance and that higher-level cognitive activities were called upon to resolve conflicts that had to be treated in a more abstract manner, we naturally decided to pursue a design approach which fostered a perceptual mode of problem solving to the degree possible.

In the VRP-TW, a strongly perceptual mode of problem solving is rendered impossible because in the traditional representation the time window information is presented numerically by placing two numbers, indicating the earliest and latest visiting times, next to each destination on the graphical map. In seeking to make these time-constraints perceptually measurable, we chose to use a three-dimensional representation of the problem, in which the third, vertical dimension represented time. The design which resulted from this approach is shown in Figure 1. The top display shows the traditional representation of the problem, here with one possible solution, in which time constraints are represented numerically. The bottom display shows the three dimensional representation of the same problem, where the route is shown traveling upward in time as it moves away from the point of origin. In this display, time windows are shown by

displaying vertical bars at each point which is time constrained. Red regions of the bar indicate times which are either too early or too late for visiting the associated point, and green regions of the bar indicate acceptable visiting times. Note from the two displays the vast difference in effort simply to make a judgment of route feasibility. In the top display, the operator must read the time at which the route visits each time constrained point, and then read the early and late times associated with this point, and ensure that the visiting time falls between the early and late times. In the lower display, the operator only has to ensure that the line showing the route does not pass through a bar at a point at which the bar is red. rather than green. Experiments confirmed that feasibility judgments were indeed made more more quickly and accurately with this three-dimensional display.

However, as seen in Figure 2, the benefits of shifting the information processing burden to perception is greatly reduced when the problem becomes so complex that clutter and masking make the required perceptual judgments difficult to perform. Although, as shown on the lower display, subjects were able to rotate and tilt the problem representation, when 35 time windows were present it was extremely difficult even to make feasibility judgments with the three dimensional display. We thus sought a design solution which exploited the benefits of graphical representation of time window constraints but did not result in unacceptable levels of clutter and masking.

Our solution to this problem is shown in Figure 3 which shows the VRP Solver system. In the colored, circular portion of this display the top-down view of the layout of destinations is shown as on the traditional VRP-TW display. However, the VRP solver system also includes (at the bottom) a graphical display that once again shows time in a vertical dimension. In this portion of the display, the current route (the current solution at some point in the problem solving process) is shown as a line from the origin point in the lower left corner, to the last city at the right of the X-axis, at increasing heights on the Y-axis indicating the times at which each of the points along the route are reached. Vertical bars are used to indicate feasible times at which the points can be visited (black areas indicate times which are too early or too late). The color of each of the bars is identical to the color of the region of the point's location in the upper map representation. This consistent coding allows problem-solver to better associate the information contained within the two representations. As indicated by the menu of options at the left side of the screen (and can be better seen in the line drawing shown in Figure 4), the problem solver can take actions such as moving a point to a different place within the route, group and ungroup points so they can be moved together as a unit, add and delete points from the current route, etc. In addition, a local improvement option can be engaged (via the Improve item in the menu) which allows the problem solver to have the computer make improvements to the route based upon an optimization algorithm.

Experimentation

Figure 5 summarizes the differences between the traditional (Table) display and the VRP Solver (Graph) display in terms of the types of inferences that must be made in order to solve the VRP-TW. As indicated by the figure. the Graph display was designed to make many of the necessary inferences performable in a perceptual fashion. In order to evaluate the potential benefit of this design approach, an experiment was performed using 10-subject groups, performing on either the baseline Table display or the VRP Solver graphical display. Subjects were required to create routes as short in distance as possible while meeting as many time constraints as possible.

Results

Figure 6 (top) shows that subjects using the graphical display produced routes with a significantly lower percent of points visited late. More striking was the finding that subjects using the graphical display produced routes with a total lateness approximately one-fifth that of the routes produced by the subjects using the table display (total lateness was measured as the sum of the amount of time late at each point over the entire route). These findings provide some support for a design approach for complex routing problems which attempts to shift information processing burdens to the perceptual system.
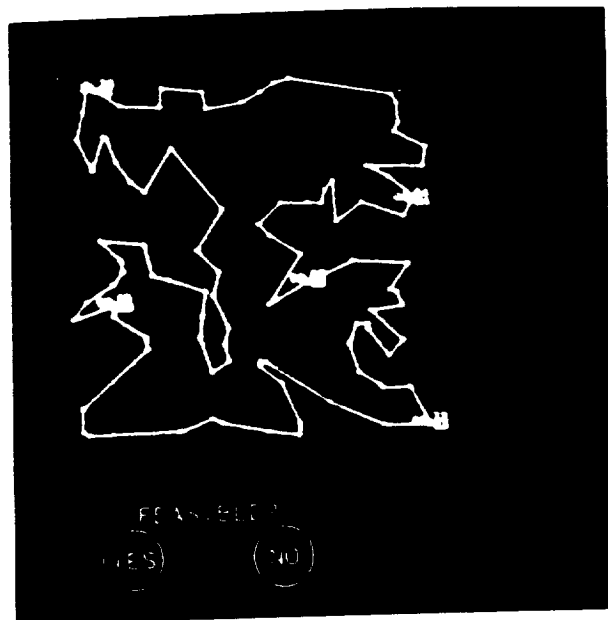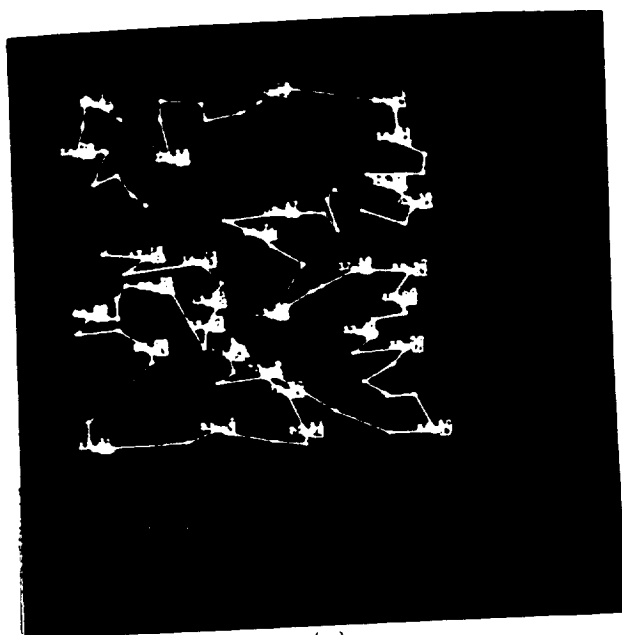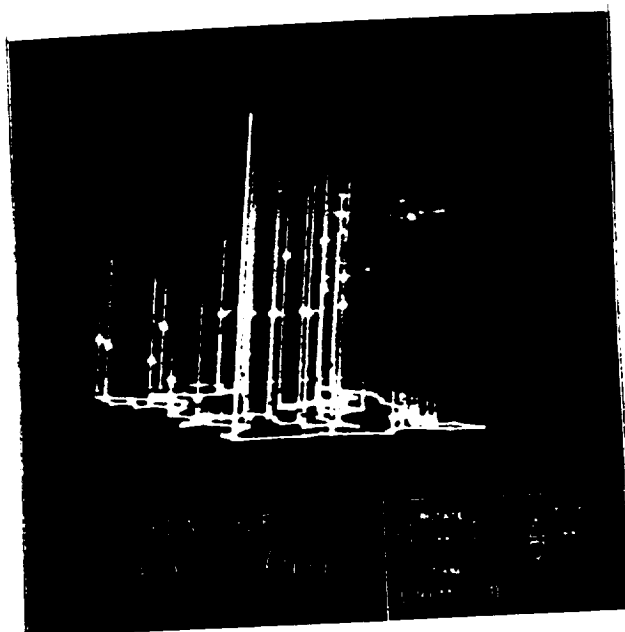
(a)
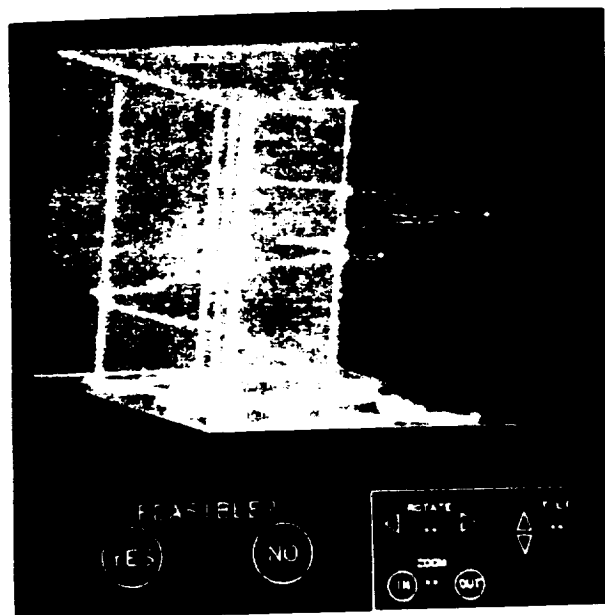
(b)

Time Windows on (a) 2D and (b) 3D Displays
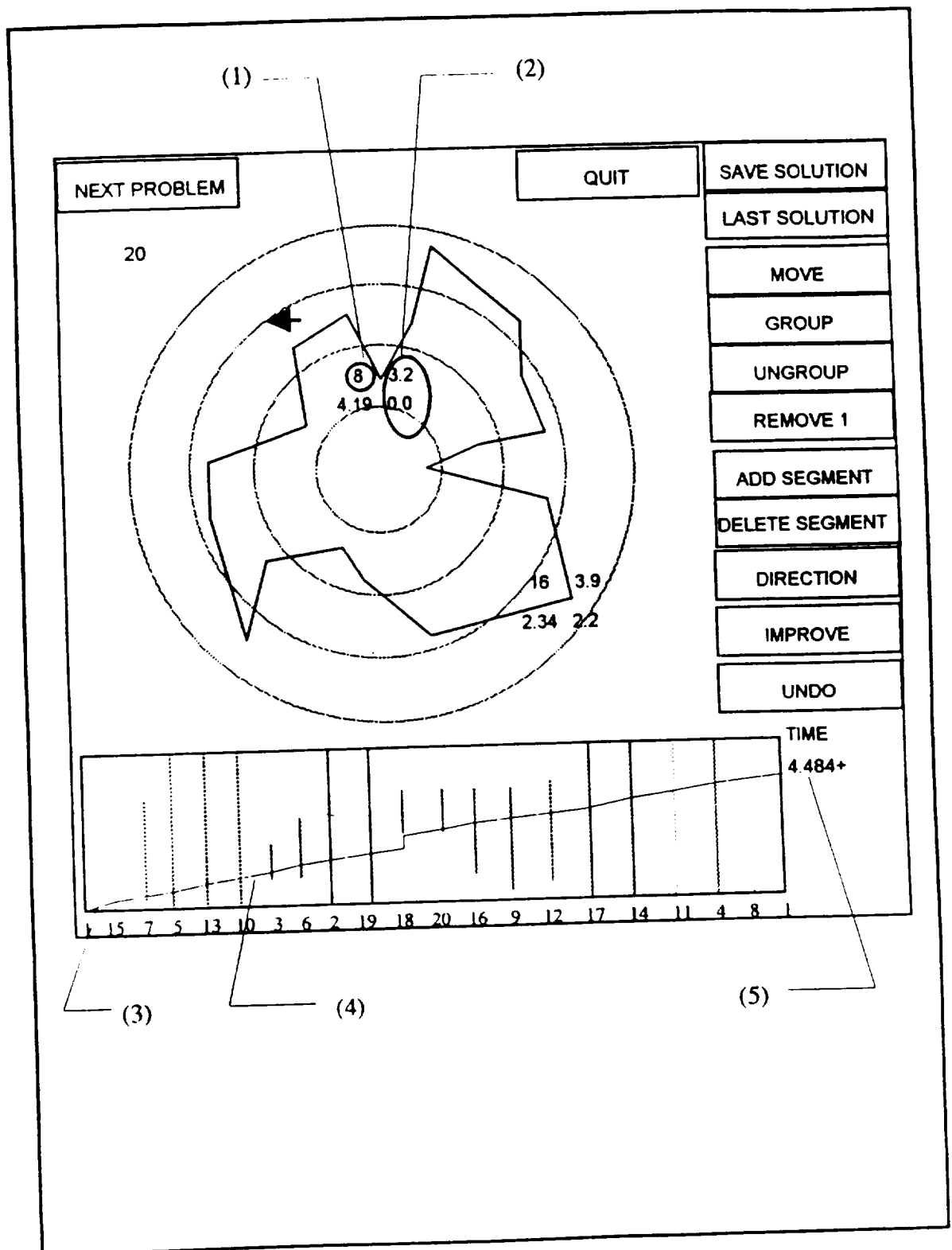(Five Time Windows)

(a)

(b)

35 Time Windows

VRP Solver: An Interactive System for Solving the VRP/TW Visually.

VRP Solver: An Interactive System for Solving the VRP/TW
(Line Drawing).

Inferences Required to Solve the VRP/TW & Information Provided
in the Two Display Conditions.

	INFERENCE	GRAPH DISPLAY	TABLE DISPLAY
IDENTIFY CUSTOMERS	What is late	Route line passes above	Table entry in red
	What is most late	Distance from route line to customer	Difference between arrival time and latest time
	What is early	Route line jumps up to customer	Two entries in yellow
	What is very early	Distance of jump up to customer	Difference between arrival times in first and second entry
	Most constrained (narrow)	Length of customer line	Differences between listed latest and earliest times
	What takes precedence	Comparisons among customers	Listed latest, earliest, and arrival times of TWs
	Is there a pattern	Relative size and location of customer lines	
REVERSAL	Is reversal potentially beneficial	Patterns of narrowness & lateness Location of customers	Color of entries, listed latest earliest, and arrival times.
	Will there be a negative impact		
DETERMINE NEW LOCATION	How much earlier/later	General slope of route line, distance from customer line, color of length of customer lines, and location of route line with respect to other TWs.	Listed latest, earliest, and arrival times.
	Effect on other customers		Number and location in table of red/yellow entries
EVALUATE ROUTE	TWs met that were not	Location of route line with respect to TWs, length of customer lines, distance between customer line and route line.	Number and location in table of red/yellow entries.
	TWs no longer met		Listed latest, earliest, and arrival times.
	More or less difficult to meet TWs.		

Mean Dependent Measure by Display